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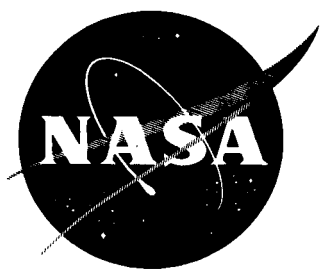
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A DESIGN OF ELECTRIC MACHINERY
FOR LONG TIME ATTITUDE CONTROL OF SPACE VEHICLES

By

D. L. Teuber   25 Feb. 1963

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ABSTRACT   /3 0 6 4

The requirements of space environment demand new developments in
the design of electric machinery. New aspects for the classical fields
of electric machinery result from the combination of semiconductors with
rotating electromechanical energy converters. An actuator is described
that is to work in a control system in which an angular impulse acting
on a vehicle is counteracted by the acceleration of a flywheel in each
of three mutually perpendicular axes. The system will work in a vacuum
and provide a torque proportional to the sum of error and rate of error
signal.

The concept of the electronic commutator eliminates brushes; the
position of the rotor with respect to the stator windings is sensed and
energized through an amplifier system that switches the corresponding
stator winding. A high efficiency is obtained by matching back electro-
motive force (EMF) and applied voltage in four concentrated windings in
addition to the use of a permanent magnet and a relatively wide air gap.
The desired control characteristic of a torque independent of motor speed
but proportional to a signal is achieved by feedback loops and a constant
current output of a d.c./d.c. inverter.

The result of the development work is a system of high efficiency
combined with circuit simplicity. Electric machines in an effective
combination with transistors can be provided for long time attitude con-
trol of space vehicles.

A U T H O R

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FOR LONG TIME ATTITUDE CONTROL OF SPACE VEHICLÉS

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D. L. Teuber

APPLIED RESEARCH BRANCH
ASTRIONICS DIVISION

ACKNOWLEDGEMENT

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A DESIGN OF ELECTRIC MACHINERY
FOR LONG TIME ATTITUDE CONTROL OF SPACE VEHICLES

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SUMMARY

An actuator is described that is to work in a control system in which an angular impulse acting on a vehicle is counteracted by the acceleration of a flywheel in each of three mutually perpendicular axes. The system will work in a vacuum and provide a torque proportional to the sum of error and rate of error signal.

The result of the development work is a system of high efficiency combined with circuit simplicity. Electric machines in an effective combination with transistors can be provided for long time attitude control of space vehicles.

INTRODUCTION

New requirements dictated from a radical change in environment and the combination of different fields of technology are leading to new developments in the field of electric machinery. Here it is mainly the application of semiconductors that benefits the performance of rotating electromechanical energy converters.

We shall consider the case where the energy stored in batteries must be transferred into kinetic energy stored in a rotating mass. This applies to an attitude control system for space vehicles in which an angular impulse acting on the vehicle is counteracted by the acceleration of a flywheel in each of three mutually perpendicular axes. Furthermore, the system should be able to work in a vacuum for several months. A coarse system, that is a mass ejection device or jets, compensates for relatively high angular impulses. The limit of the machines is imposed by their compatibility with the power supplies and the transistor electronics at about 1 kW.

ENERGY CONVERSION

Basically, there are two approaches to the energy conversion (FIG. 1). A "conventional" induction or self-starting synchronous motor driven

from a static inverter can be used. The speed n of the machine in both directions is regulated from the input ($\pm\epsilon$) to the amplifier system. For full utilization of the motor, the voltage applied to it is changed in proportion to the frequency except below about 1/10 of the normal frequency. Thus the field in the motor will remain constant.

In the other case, the motor with transistor commutator provides its own frequency from a position sensor. The rotor position signal for controlling the switching action of transistors is obtained by rigidly coupling this position sensor to the machine. The tachometer can be used in both cases for control purposes to provide a feedback signal and the direction of rotation.

A comparison of merits of both systems is rather involved since in any case several stages of amplifiers are used that must be considered in the process of energy conversion (Ref. 1). All of the induction or synchronous motors cannot be efficiently controlled in speed unless the power is provided with varying frequency and voltage. When running asynchronously, induction and hysteresis motors require predominantly wattless power to build up the necessary magnetic field in addition to the power transferred into mechanical energy.

MOTOR AND TRANSISTOR COMMUTATOR

Because of simplicity and high efficiency, the motor with transistor commutator and concentrated windings was chosen. A distributed winding with an essentially sinusoidal back electromotive force (EMF) of the machine and a rectangular applied voltage from the transistor switches reduces the efficiency (FIG. 2). Furthermore, a motor with a sinusoidal flux distribution requires $\pi/2$ times more active iron than a motor with a square wave flux distribution of the same total flux. A square wave back EMF can be matched efficiently by square wave a.c. power. All the harmonics in the square wave back EMF produce a full torque with the corresponding harmonics of the square wave power supply. An ideal square flux distribution cannot be achieved because it would require a 180° pole span. However, the output of the d.c./a.c. inverter can be easily matched to the flux distribution curve, thus saving some active iron in the drive. The layout concept approaches that of a conventional d.c. motor (Ref. 2). The commutator and brushes represent a mechanical d.c./a.c. inverter and are replaced by electronic components.

The concentrated windings can be energized in two different ways by the d.c./a.c. power inverter (FIG. 3). Eight switches are in the schematic of the motor drive shown in FIGURE 3a; all copper is utilized for both half waves. In FIGURE 3b, there are only 4 switches using 1/2 of the copper for both half waves. It is felt that the use of all copper in the first system does not justify twice the number of power switches; however, there is a way to utilize the motor shown in FIGURE 3b for regenerative braking without doubling the number of switches.

Since each branch can energize the system only for somewhat less than 180° and since a torque in any angular position is required for self-starting of the machine, a minimum of 3 branches is needed (FIG. 3c). However, to use the same circuitry for both directions of speed, 4 branches were selected as shown in FIGURE 3b; thus the number of electronic components was kept to a minimum.

The actuator is sufficiently well specified for control systems investigations by the moment of inertia of the rotating mass and by the speed-torque curves n = f(T) with the error signal as the parameter. A desired characteristic is shown in FIGURE 4 where the accelerating torque is independent of the flywheel speed and proportional to the control signal.

MECHANICAL AND ELECTRICAL LAYOUT

The mechanical design of the actuator is shown in FIGURE 5. For better utilization of the masses, a rotating permanent magnet with a stationary armature inside was selected. The shaft is hollow for the armature windings. Rotating are two shields separating the laminated pole shoes, pole pieces, and two permanent magnets as ring segments made of ALNICO V. The design combines a low weight of the machine with a high moment of inertia to weight ratio. An unusally large air gap was chosen to suppress the reaction of the flux generated by the armature currents on the flux of the permanent magnet. Armature reaction increases the losses and defeats the purpose of matching a desired rectangular back EMF with square waves supplied from the transistor amplifier. The position pickup consists of four resonant circuits. It is mounted to the stationary shaft of the machine and the rotating mass. A segment periodically changes the tuning (f_o = 60 kHz) of an LC-network proportional to the speed and in any position at standstill. Power transistors at the third stage of an amplifier activate the respective armature winding as the flywheel accelerates from standstill to 10 000 RPM within 300 seconds and a torque of 500 cmg. About 50% of the energy delivered from the battery is finally stored in the energy of the flywheel.

The control and commutator circuitry contains transistor amplifiers in a switching mode, oscillators, a magnetic push-pull amplifier for isolation, and mixing signals. Flip flops, AND, and OR circuits are used for torque reversal. Signals are provided to a computer for activation of the coarse nozzle control system. In the general case, the nozzles will fire under a combination of three signals (in amplitude and direction) per controlled axis. The three signals are flywheel speed, angular error, and rate of angular error.

FIGURE 6 shows the basic setup of the actuator with the electronics. The d.c./d.c. inverter consists of transistor switches that work in pulse duration modulation. The switching of the inverter is adapted to

a pole span of 160° of the machine. This value has been selected to limit the leakage flux from pole to pole; thus the battery voltage is changed to the required actuator voltage. The negative feedback around the inverter makes it essential to a constant current source. The output is independent of load variations; the maximum current is limited to a preset value. This and two friction compensation inputs (one constant, the other proportional to speed) provide for a motor torque which is proportional to the geometric sum of error and rate of error ($\phi + \dot\phi$) and independent of the motor speed (similar to FIG. 4). Actual and desired speed are compared in a logic circuit, and a torque reversal is achieved by 180° phase shift of the commutator signal with respect to the rotor position. (If the sequence of the resonant elements was 1 2 3 4, it is then 1 4 3 2 providing a counterclockwise rotation.) The requirement for the forward direction $F = AC + \overline{AB}$ and for the backward direction $F = A\overline{C} + \overline{AB}$ in Boolean logic is shown in FIGURE 7. The condition is mechanized by standard transistor elements.

REGENERATIVE BRAKING

For braking the motor, it is required to dissipate energy from the flywheel either by burning it in resistors or feeding it back to the batteries. The regenerative braking is used without feedback loops as shown on the schematic in FIGURE 8. The choke and capacitor are for filtering the output of the PDM system. For reasons of simplicity of the commutator circuitry, the current flow in the actuator is in one direction only. The trick of the regenerative braking is in the arrangement of the diodes across the pulse duration modulated transistors. Ordinarily, without the flow of energy back into the batteries, one diode would have to be used to protect the transistor switches from back voltages caused by the choke. With just one more diode as shown in FIGURE 8, regenerative braking is possible. The equilibrium between V_C (choke voltage), V_B (battery voltage), and V_M (effective motor EMF) is also indicated for the switch-on phase and the switch-off phase of the pulse duration modulated inverter. It can be seen that the actuator continuously produces mechanical work in the driving condition. The battery will be charged in the braking condition. The speed-torque curves approach those of FIGURE 4 with a maximum deviation of not more than 7%.

APPLICATION OF THE ACTUATOR

The actuator is being used on a satellite motion simulator as described in Reference 3. For this purpose, the flywheel has been enclosed by a capsule under low pressure to reduce windage losses (FIG. 9). Chamber pressures of about 0.05 kg/cm^2 reduce the aerodynamic losses at 10 000 RPM into the range of bearing friction. The bearings are slightly preloaded in axial direction to avoid a shift of masses. Vibration calculations and measurements show that the critical speed of

the rotating flywheel lies well beyond the operational speed. The heat loss is removed from the pressure chamber by heat conduction and radiation through shaft and housing.

The cover plate of the box with the circuitry for one motor (P2) has been removed for FIGURE 9. The components of the various elements are mounted on cards and can easily be removed for adjustments. Essentially all elements that can be seen are working together according to FIGURE 6. The computer connecting to "sign of speed" and "amplitude of speed" is not shown in FIGURE 6. These two signals are recorded at the same time through a telemeter system that is mounted on the satellite motion simulator. A radio link must be used for this purpose since connecting leads to the satellite motion simulator would create disturbance torques.

It would exceed the scope of this report to describe the connection of both motor and nozzle control in three axes through the computer, the position sensing optics, and their combined action. However, because of the combined system dynamics, a speed-torque characteristic of FIGURE 4 is desirable such that the correcting motor torque is proportional to the signal controlling the torque.

CONCLUSIONS

A rotating electromechanical energy converter has been developed that combines off-standard techniques in the design of electric machinery with transistor circuitry in a unique system. An electronic commutator allows operation in a vacuum; regenerative braking prolongs the lifetime of batteries. A speed-independent torque that is proportional to the control signal provides the precise attitude control of a satellite motion simulator in a fine range, supplementing the nozzle control in a coarse range. On the basis of these results, attitude control of space vehicles can be provided.

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FIGURE 1b   MOTOR WITH TRANSISTOR COMMUTATOR
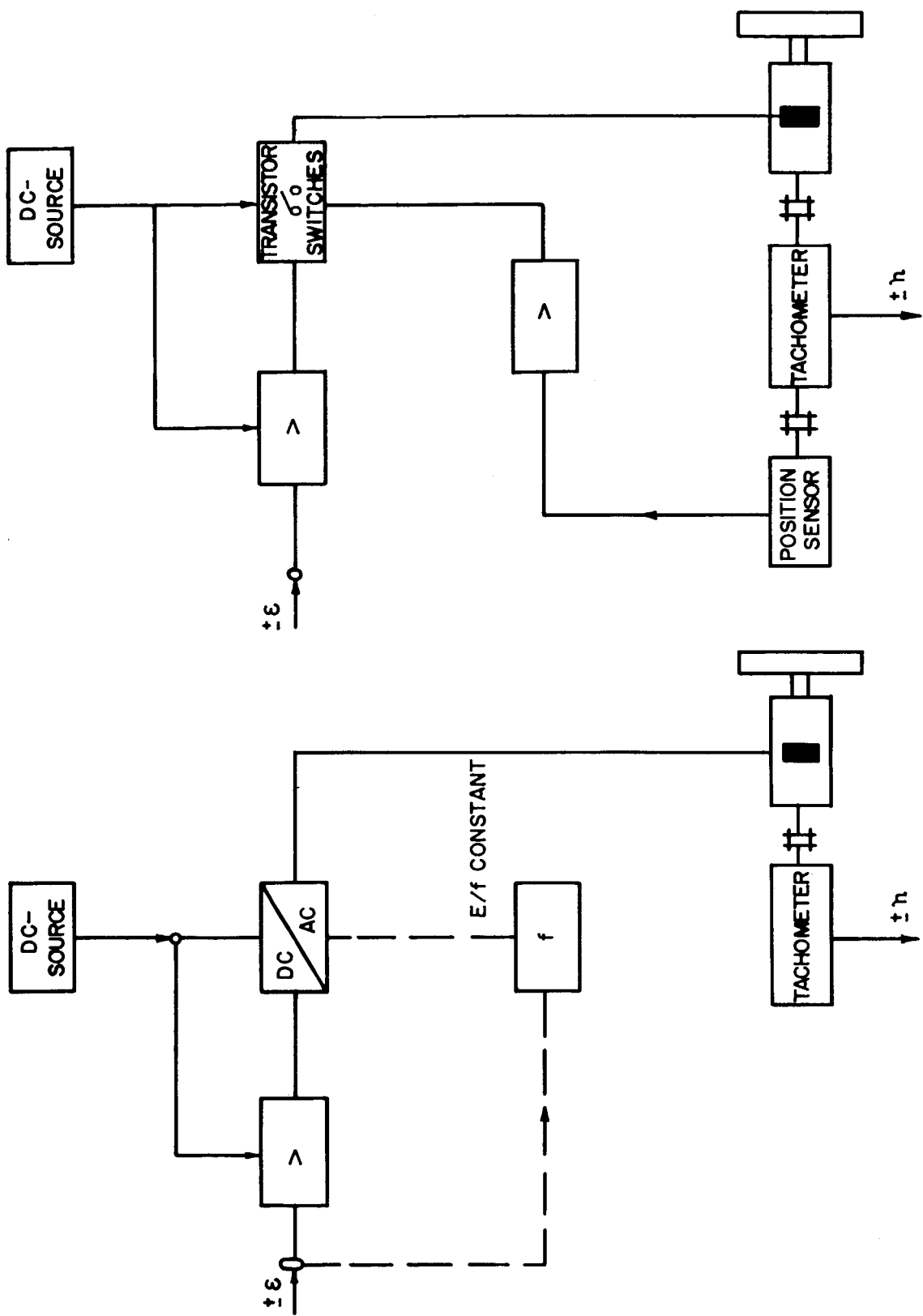
FIGURE 1a   INDUCTION OR SYNCHRONOUS MOTOR
DRIVEN FROM STATIC INVERTER
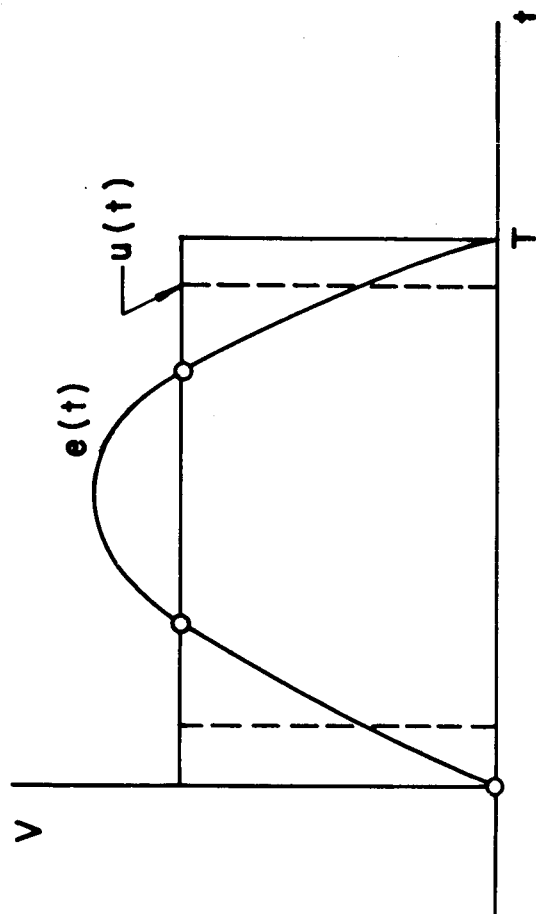
$$i = \frac{u - e}{r}$$

$$\eta = \frac{\int_o^T eidt}{\int_o^T uidt}$$
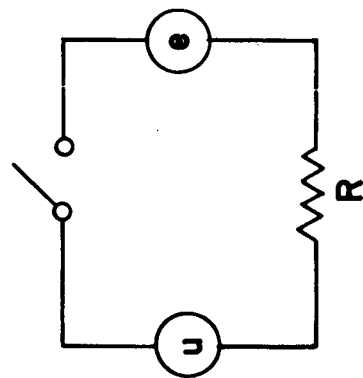
FIGURE 2 SINUSOIDAL BACK EMF e(t) AND RECTANGULAR APPLIED VOLTAGE u(t)
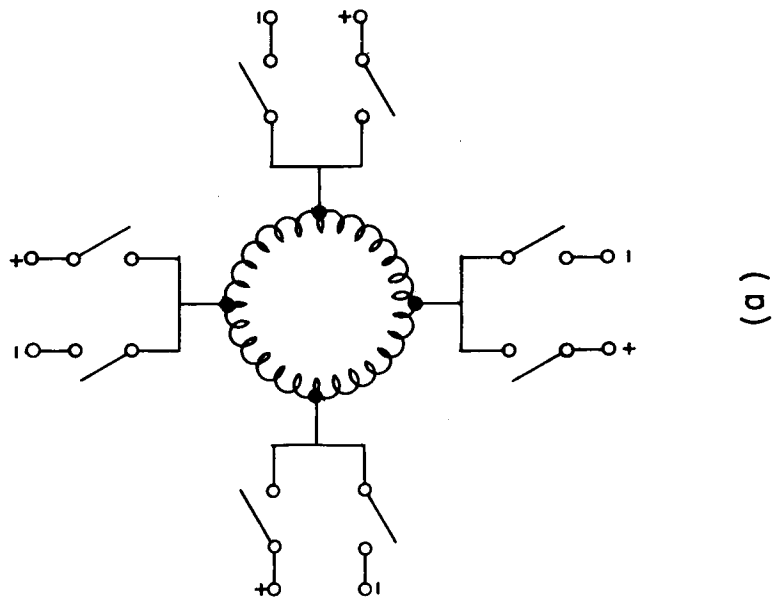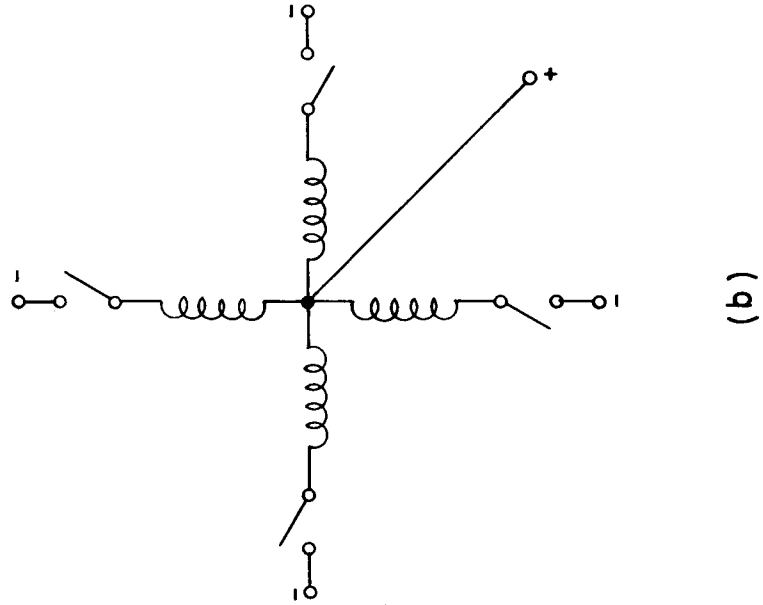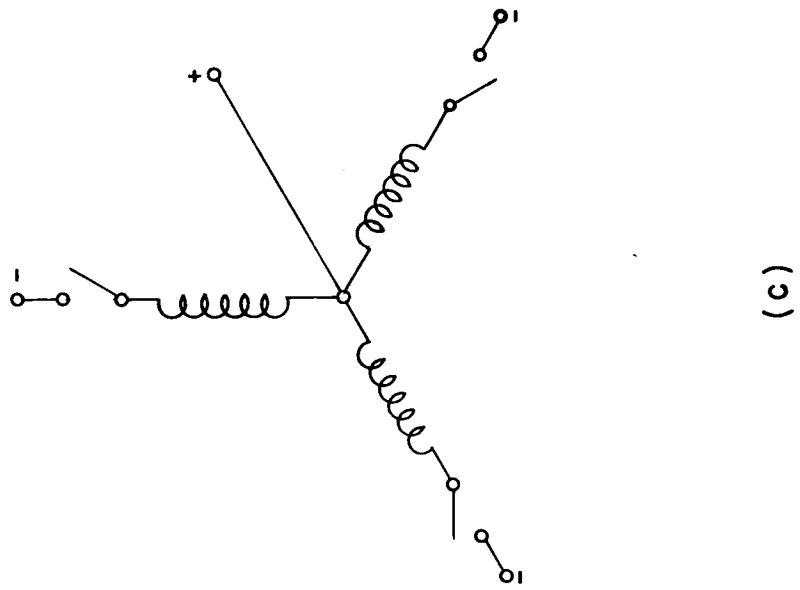
(c)

(b)

(a)

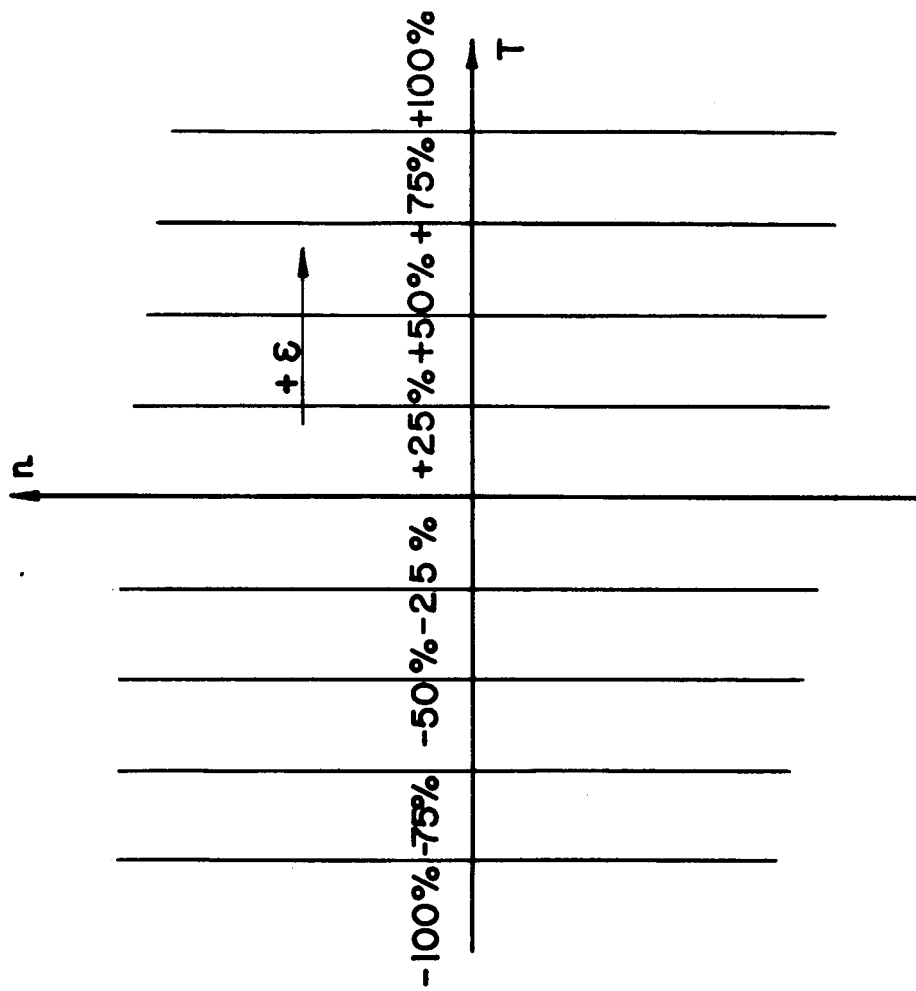**FIGURE 3**   **THE DRIVE CONCEPT**

$$n = f(T)$$

FIGURE 4   DESIRED CONTROL CHARACTERISTICS

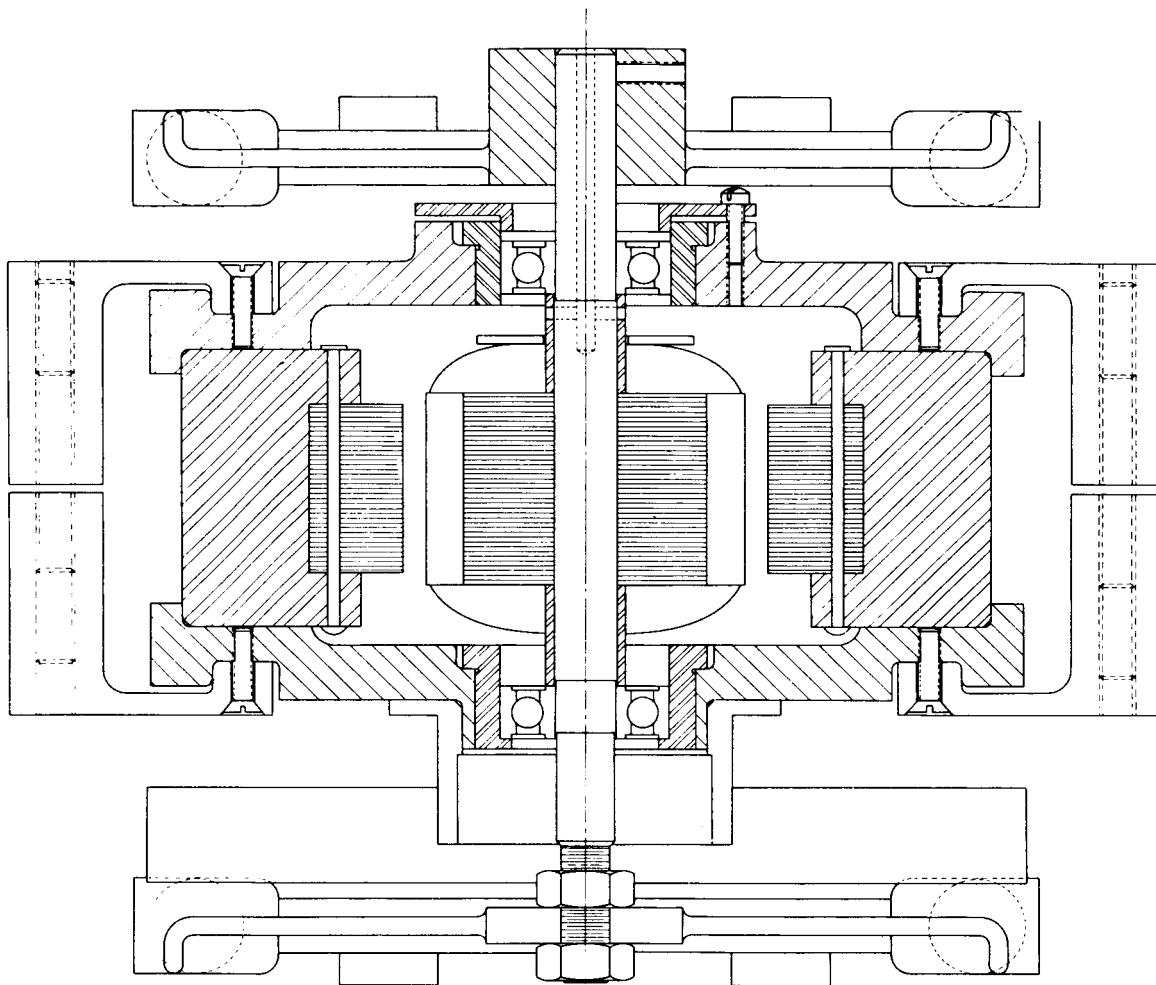**FIGURE 5 | THE ACTUATOR DESIGN**
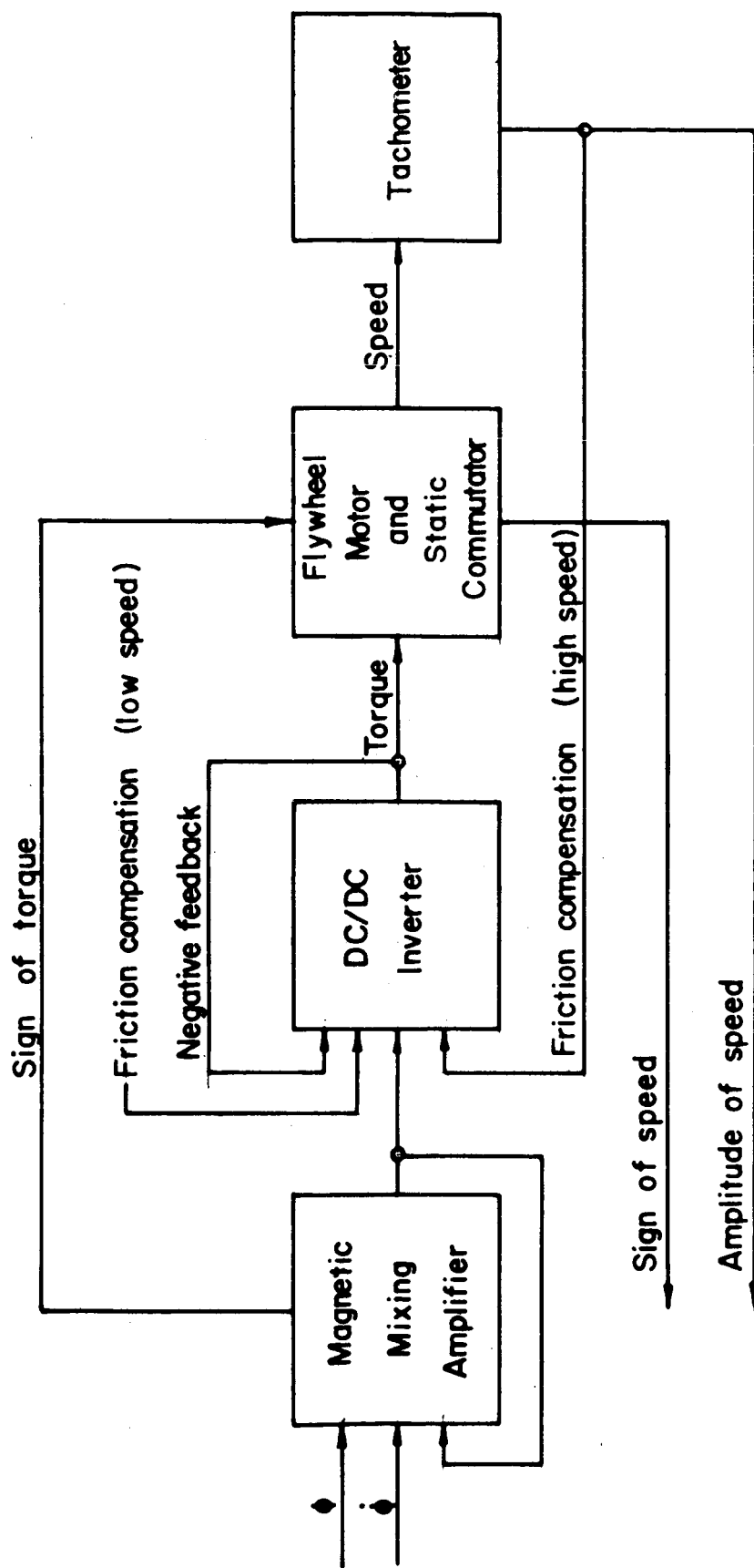
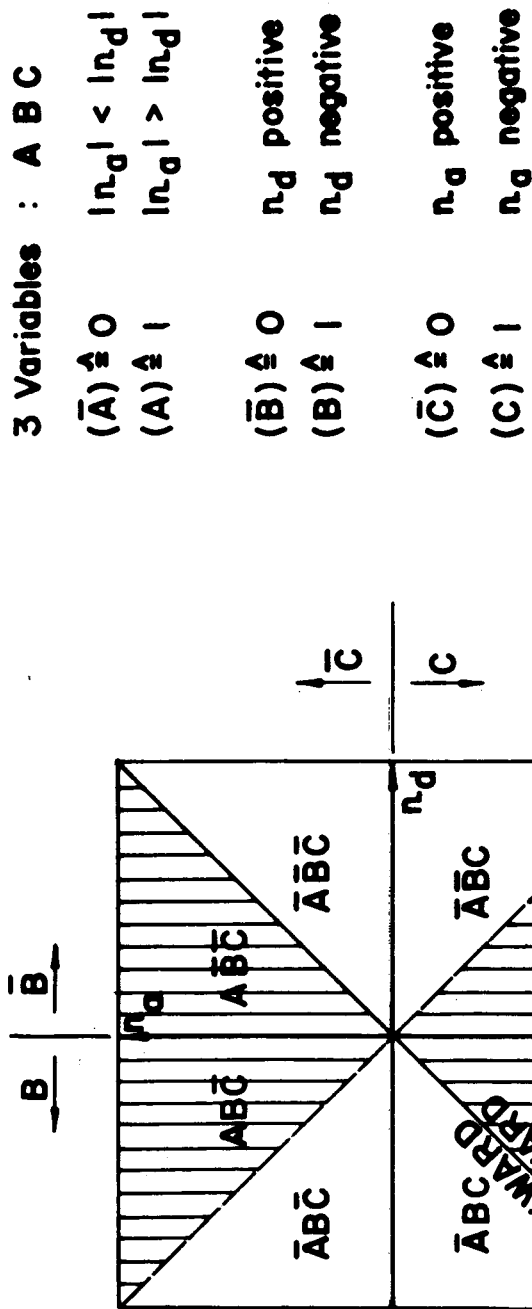FIGURE 6   BASIC SETUP OF ACTUATOR AND ELECTRONICS

$n_a \longrightarrow$ actual motor speed
$n_d \longrightarrow$ desired motor speed
shaded area $\longrightarrow$ A

3 Variables : A B C

$(\bar{A}) \triangleq 0 \quad |n_a| < |n_d|$
$(A) \triangleq 1 \quad |n_a| > |n_d|$

$(\bar{B}) \triangleq 0 \quad n_d$ positive
$(B) \triangleq 1 \quad n_d$ negative

$(\bar{C}) \triangleq 0 \quad n_a$ positive
$(C) \triangleq 1 \quad n_a$ negative

SPEED
DIRECTION
LOGIC

$\begin{cases} F = \bar{A}\bar{B}\bar{C} + \bar{A}\bar{B}C + AB\bar{C} + ABC = AC + \bar{A}\bar{B} \\ \bar{F} = A\bar{B}\bar{C} + A\bar{B}C + \bar{A}B\bar{C} + \bar{A}BC = A\bar{C} + \bar{A}B \end{cases}$

FIGURE 7 SPEED DIRECTION LOGIC

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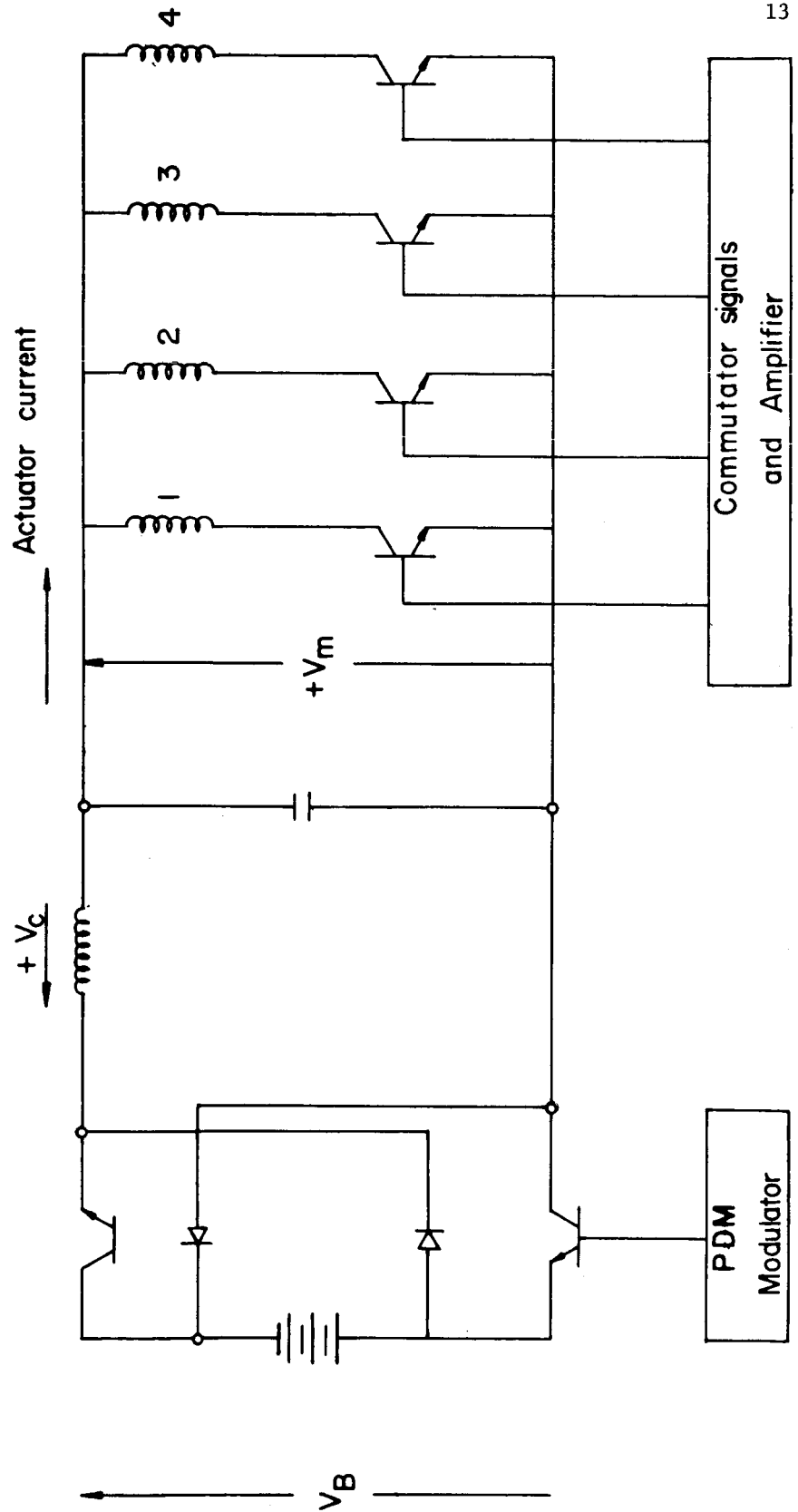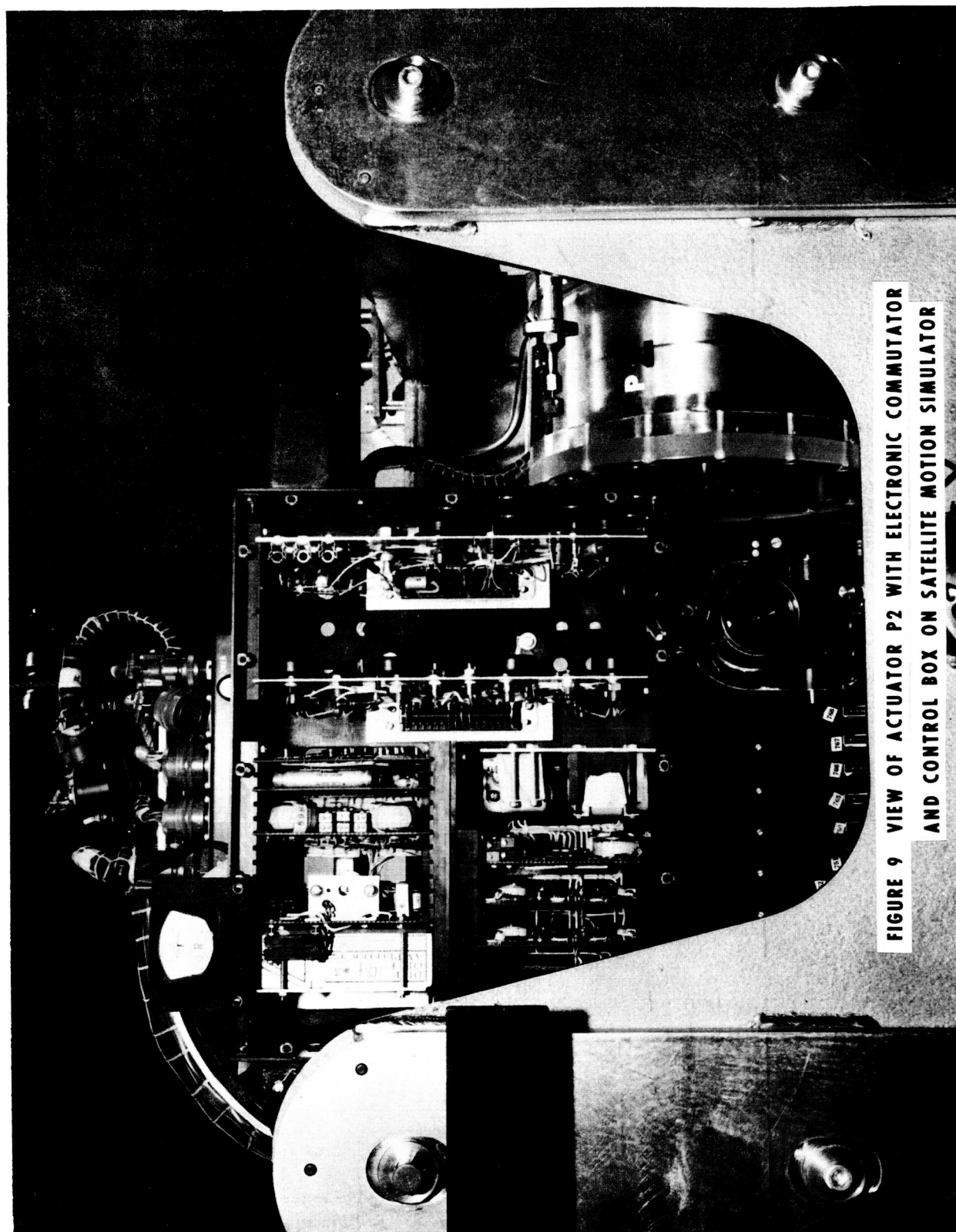|	Driving	Braking
PDM on-phase	$V_c = V_B - V_m$	$V_c = V_B + V_m$
PDM off-phase	$V_c = -V_B - V_m$	$V_c = -V_B + V_m$

FIGURE 8 SCHEMATIC FOR REGENERATIVE BRAKING

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FIGURE 9 VIEW OF ACTUATOR P2 WITH ELECTRONIC COMMUTATOR AND CONTROL BOX ON SATELLITE MOTION SIMULATOR

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APPROVAL MTP-ASTR-R-63-3

A DESIGN OF ELECTRIC MACHINERY
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By

D. L. Teuber

The information in this report has been reviewed for security
classification. Review of any information concerning the Department
of Defense or Atomic Energy Commission programs has been made by the
MSFC Security Classification Officer. This report, in its entirety,
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